PULSED ELECTROMAGNETIC INDUCTION (PEMI) FOR UXO DISCRIMINATION IN JPG PHASE IV — PRELIMINARY RESULTS

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ABSTRACT

The high false alarm rate in unexploded ordnance (UXO) detection using standard magnetometric, electromagnetic induction, and ground penetrating radar methods motivate the development of novel remote sensing techniques that provide greater target discrimination ability. The Pulsed ElectroMagnetic Induction method (PEMI) shows much promise for localization, characterization, and identification of UXO, as demonstrated in an evaluation project carried out by APL-UW in 1995. The project included development of a set of PEMI models for simulation and data reduction, development of a testbed PEMI system and data processing tools, and several stages of field work in which the models were validated and responses from several inert UXO samples were measured. Finally, four inert buried UXO targets at a NAVEODTECHDIV test site were located and successfully characterized.

The JPG Phase IV project provides an opportunity to collect data from a wide variety of UXO targets in realistic conditions using a PEMI testbed system. Commercially available instruments often make significant compromises in response data collection in favor of manufacturing a rugged field portable system. The 1998 APL-UW work seeks to demonstrate the discrimination and classification capability of the PEMI technique by collecting detailed target responses, in time and space. In support of that objective, modest improvements to the existing PEMI testbed and data analysis software were proposed to render the system more practical to use under field conditions. These include design and construction of a mobile battery powered transmitter, automatic receiver position sensing and recording, and data processing software for rapid preliminary results. The PEMI approach is outlined, our modified PEMI system is described, and a preliminary field test conducted at JPG during the week prior to the Forum is summarized.

I. Introduction

A. Technical / Operational Need

Millions of acres of US government soil are contaminated with UXO. Additionally, UXO and landmines pose a threat to US military and civilians in many foreign regions. Remediation and clearance of contaminated sites is dangerous and expensive, and a significant part of the cost is due to the very high false alarm rate incurred by all currently available sensors.

There is a current need to provide a fieldable sensor that efficiently provides reliable discrimination information in the UXO detection problem. The sensitivity and specificity requirements vary greatly from site to site, some targets being large and deep (e.g. 2000 lb bomb at 5 m depth) and others being small and shallow (e.g. landmines). While it is generally accepted that no single sensor will be adequate in all applications, a versatile technology that can be scaled according to target response and from a small handheld unit to a larger device for use on a (remotely operated) vehicle is desirable.

B. Existing Capability

The false alarm rate of all existing UXO sensing tools is unacceptably high. The three most promising technologies for UXO detection are GPR (ground penetrating radar), Magnetometer, and EMI (electromagnetic induction). GPR has the potential of long standoff imaging of the earth's subsurface but is very sensitive to small changes in soil properties which give large clutter signals. Magnetometer methods are inexpensive and passive but can only detect ferromagnetic objects and also suffer from poor discrimination between clutter due to magnetic soils or shell fragments and UXO targets. EMI methods are active and can induce currents in any conductor (i.e. not just ferrous metals), and operate at relatively low frequencies compared to GPR and therefore are not affected by soil variations. Pulse EMI methods (PEMI) can measure target responses over a wide band of frequencies at once. The pulse response has been shown to provide good classification information between different targets and provides a very useful tool in discriminating UXO from metallic clutter. Currently used "metal detector" designs are either single frequency devices or pulse devices which do not take advantage of the full target response thereby not utilizing the full discrimination capability of the PEMI method.

C. Results of previous work by APL

In FY95 the AEC and NAVEODTECHDIV funded APL-UW (under a subcontract with Alliant Techsystems, now a division of Raytheon) to evaluate the Pulse Electromagnetic Induction (PEMI) method in the UXO application. Earlier uses of pulse EMI signals in environmental and UXO applications did not take full advantage of the pulse response to provide target discrimination capability in the way that was commonly done in mineral exploration geophysics. The FY95 project included modeling UXO target responses and PEMI system performance, assembling a PEMI hardware testbed system and measuring response from several inert UXO shapes as well as some machined test targets, and finally performing a test survey on a realistic UXO range at the EOD base in Indian Head, Maryland.

The APL-UW FY95 project demonstrated that simple target response models are very effective in PEMI performance modeling and field data analysis and interpretation. These models and data processing algorithms are simple enough to do real time interpretation in the field. The pulse response contains a lot of information about the target construction; in the FY95 project only one feature of the complete response was used to classify targets (the late-stage decay time constant). Even so, this one parameter allowed discrimination between two types of UXO independent of location and orientation (80 mm Vs 155 mm shells which have 15 ms and 30 ms decay constants, respectively), and between buried UXO (of type unknown to contractor) and other metallic objects (clutter) on the EOD test range with 100% success for four UXO targets.

The current limitation of the technology is that a practical PEMI system, designed specifically for the UXO application, does not exist. (Existing geophysical systems are not practical and/or effective for UXO or landmine surveys.) This limitation prevents the technology from being demonstrated to and evaluated by field EOD personnel for further refinement and widespread use. The work proposed here is to adapt the techniques demonstrated in the FY95 program to the design and construction of a few key components of the PEMI system processing, as well as demonstration at the Phase IV JPG test. The technology developed in this program could readily be modified to be taken to commercial production for man portable or vehicle mounted instruments.

II. Objectives of this project

A. Demonstration of the PEMI method's discrimination capability

JPG IV provides an excellent opportunity to demonstrate the discrimination capability of the PEMI technique applied to the UXO detection problem. Previous JPG demonstration phases specified an area coverage rate that required mature field-ready systems. The original APL-PEMI system had been developed for method evaluation and proof of concept purposes and was not suited for efficient field deployment. This Phase IV program emphasizes the demonstration of discrimination ability rather than rapid area coverage for UXO detection and thus presents an ideal opportunity to evaluate the PEMI method in a realistic environment with a large set of buried test targets. Nevertheless, since the FY95 APL program did serve to characterize UXO target responses, a prototype system design tailored to the UXO problem can now be made. Such a prototype should be able to minimize the required bandwidth of the transmitter and receiver systems. Consequently, the system can be less expensive and more efficient than a COTS (Commercial Off-The-Shelf) solution using system components designed for other purposes.

B. PEMI Field System Upgrade

The original PEMI testbed was designed to be highly programmable and uses off-the-shelf laboratory and geophysical field instruments. The testbed was instrumental in evaluating the system parameters of a UXO prospecting system and it was determined that several subsystem components can readily be simplified and combined into an effective field instrument that is portable and efficient. The following modifications have been implemented in the construction of a light field system, illustrated in Fig. 1.

Transmitter system: The transmitter used in the FY95 program was a commercial geophysical transmitter designed to switch much faster than necessary for UXO. A battery powered design using modern IGBT switching semiconductors has been designed and built for the UXO application, namely with switching times on the order of a few milliseconds.

Receiver system: The receivers are built with fixed gains and low pass filter stages for simplicity and compactness, based on the results of the data analysis of the FY95 program. It is expected that no more than 5 kHz bandwidth will be necessary. Two new 3-axis magnetic field sensor coils will be designed into the sensor array; original sensor coils were used in the April 1998 test.

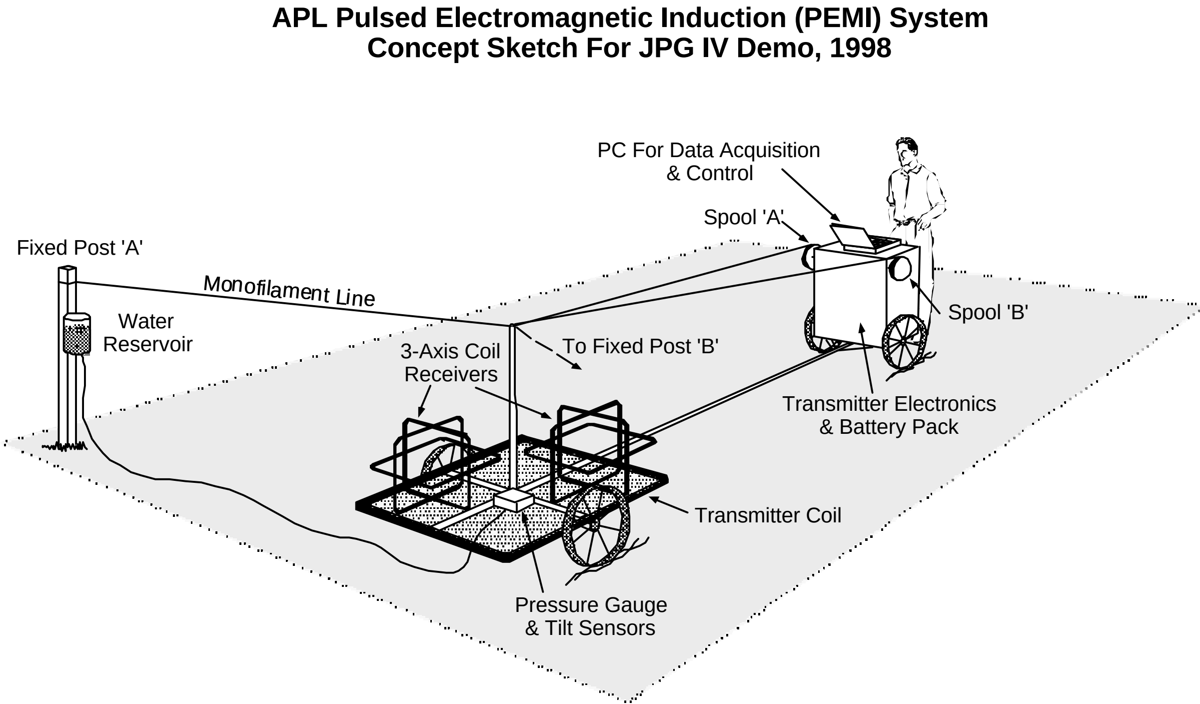

Figure 1. PEMI testbed concept sketch. Two wheeled carts carry the entire system, which is towed by an operator walking from station to station. The sensor package is comprised of the transmitter coil, two 3-axis receiver coil assemblies, a 3-axis magnetic compass and 2-axis electrolytic tilt sensor, and a pressure gauge used to measure the sensor platform's elevation. The operator's cart carries the notebook computer, the receiver signal conditioning electronics, the transmitter electronics, the positioning electronics, and the transmitter power battery pack. The entire testbed weighs about 150 lb., and is intended to be a method development testbed rather than a commercial prototype system. Nevertheless, it is totally battery powered and automated enough to make field data acquisition a reasonably efficient procedure.

Sensor platform: The 1995 PEMI testbed included a rigid platform on which the receive sensors were mounted; the 5 meter square transmitter coil was laid out on the ground. At each station the receiver platform was manually oriented and leveled, and the procedure was very time consuming. A non-conductive and non-magnetic wheeled platform has been designed to accommodate the transmitter and receiver coils, and is connected by a rigid tow bar to a second cart which will support the electronics and PC data acquisition system.

Sensor tracking system: A sensor location and tracking system (commercially available as either GPS or acoustic tracking) could be integrated into the data acquisition system for accurate positioning of each reading for later use in creating an accurately registered map of the survey results. The cost of such a system is considered too great for this proposal, and a mechanical means of measuring sensor position with respect to a point close to each target will be used instead. The local reference point(s) will be marked by a stake or flag for later tie-in to the overall site grid for mapping of responses.

Position sensing will be done with respect to a local 15 x 15 meter zone, using a compass heading reading and electrical odometers for tracking in the horizontal plane, and a liquid level system for the elevation. The two odometers will be made with 10 turn potentiometers geared to tensioned spools of light line. The lines are tied to two posts fixed in the earth, defining the local grid. Simple processing of the odometer readings is required to convert the measured arc lengths to X-Y grid coordinates. An electronic pressure transducer is used to determine the elevation of the sensor cart with respect to the fluid level in a fixed reservoir on one of the posts (a similar method was used in prior work though the level was read by eye for each station). To measure the orientation of the sensors, a pair of tilt sensors will be fixed to the platform while the azimuthal bearing will be determined from the compass heading.

Computer controller and data acquisition system: UXO PEMI responses are such that required data rates are relatively slow. A capable multichannel data acquisition system has been assembled using a battery powered PC (DELL laptop) and a commercially available analog input/output card (National Instruments DAQCard-AI-16XE-50), and using equipment available to the project from other sources at APL. The system is controlled by software written in LabVIEW®, modified from the 1995 version of the code. The data acquisition system is sketched out in Fig. 2.

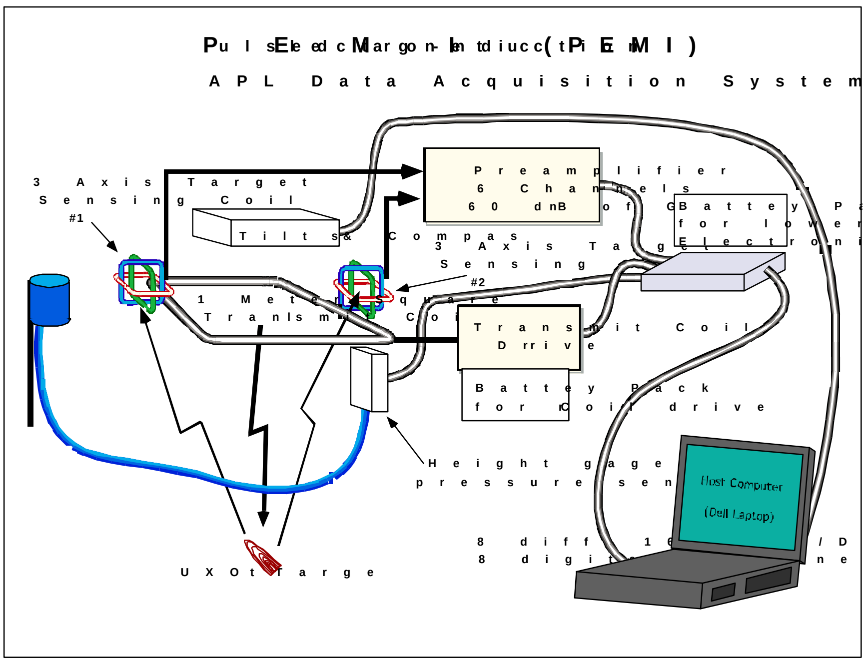

Figure 2. PEMI testbed block diagram. The main electronic components of the system are indicated. (X-Y Positioning system not shown.)

C. *Refinement of PEMI Modeling and Data Analysis*

PEMI models: The PEMI target responses are currently calculated using a fixed transmitter position for variable receiver locations. The integration of a mobile transmitter will improve field operation efficiency and the models will be modified to incorporate the new field procedure. Use of a second set of 3-axis receivers will also be integrated in the models to provide a gradiometer configuration for ambient noise reduction. Finally, a provision to extract multiple characteristic time constants from the target response data will be implemented for evaluation.

Data processing and user interface software: The target location and time constant estimation software algorithms developed under the FY95 program will be refined and integrated with an in-field processing scheme. Target classification information will be provided in near real-time at each station, and target localization information will be provided soon after enough spatial data has been collected. Finally, a map of the entire survey area including sensor track and interpretation results will be produced after completion of the survey.

III. Technical Approach

1. The PEMI method

Electrical currents can be readily induced in conductors by immersing them in a (primary) time varying magnetic field. These induced currents in turn create secondary magnetic fields which can be detected in the region near the buried conductor. The temporal and spatial variation of these secondary magnetic fields contain information about the conductor, such as its position, size, and conductivity. Studies have shown that pulse methods provide more information about the target than do single frequency methods, especially important when the response is cluttered by other conductors lying closer to the sensor. Much of the original development of the pulse induction method was done by Kaufman [1978a, 1978b]. McNeill [1980] presents a succinct exposition of the PEMI method's applications in the context of geophysical prospecting. Figure 1 illustrates a possible implementation of the PEMI method, using a large fixed transmitter coil. An alternative using a smaller transmitter coil moving with the receiver is considered in this proposal.

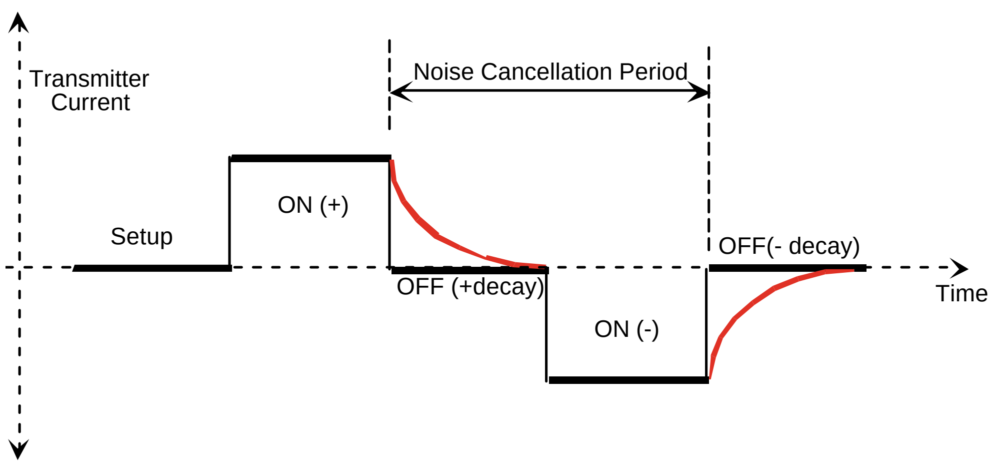

Figure 3. Transmitter pulse sequence. A bipolar pulse is used to facilitate canceling of periodic noise, especially power line noise which contains 60 Hz and higher harmonics. Spacing of the two pulses by an integer number of noise periods allows canceling the noise by inverting the second pulse and adding it to the first.

a) Primary and secondary fields

The primary current in the transmitter coil is a series of pulses as illustrated in Figure 3. During the transmitter "on" time, the current in the transmitter loop reaches a constant value, creating a constant primary magnetic field in the vicinity of the target conductor. The primary magnetic field exists in all space but is strongest near the transmitter. When the transmitter current (and thus the primary magnetic field) is turned off abruptly, a large electromotive force (emf) pulse arises in space by Faraday's law. The emf drives a current pulse in the conductor. This induced current is such that the magnetic field within the confines of the conductor is the same as it was just before turn off. Immediately after the emf pulse, resistive losses cause the secondary currents to decay with time, leading to induction of other currents further inside the target.

b) Three stages of the pulse response

The pulse response of a confined conductor is conveniently divided into three time intervals, each of which corresponds to a different physical regime. At turn off, currents form on the outside of the conductor in such a way as to exactly preserve the magnetic field that was inside the conductor before turn off. In the very early instants after turn off, the induced currents are confined to the outermost parts of the conductor. This is consistent with the idea that early times correspond to very high frequencies, and at high frequencies the skin effect prevents currents from penetrating into the conductor. In this **early time** stage, it is clear that the current distribution depends on the primary field and on the external shape of the conductor, but is relatively insensitive to the target's conductivity.

The surface currents are soon attenuated by resistive losses, and because they change with time they begin inducing other currents circulating further inside the conductor; as time progresses, the distribution of currents changes to include the entire conductor. This diffusion of currents happens during the **intermediate time** stage.

In the **late stage** however, the spatial distribution of currents in the conductor no longer changes, and all currents merely decay at the same exponential rate. The time constant characterizing this late stage exponential decay is determined by the overall construction (shape, material conductivity and permeability) of the body. In the case of metallic objects made from the same metal the conductivity is the same; consequently, only the shape determines the exponential time constant. For solid cylindrically symmetric bodies, a simple conductive loop circuit with inductance L and resistance R, is often a satisfactory late stage model. Indeed, a current in such a loop decays exponentially, with decay constant $t = L/R$. The late stage behavior for confined conductors allows straightforward characterization of the conductor from measurements of the secondary magnetic field which decays with the same exponential time dependence.

The *amplitude* of PEMI target responses depends on transmitter and receiver coil location and orientation, but the *time rate of decay* of the response does not (barring special geometric cases in which the object and field are precisely aligned so as not to excite the fundamental mode of the target's response). The decay rate depends only on important intrinsic (and macroscopic) target parameters such as shape and conductivity, and can thus be used to discriminate quantitatively between different objects.

Kaufman [1978a] showed that the complete pulse response of a conductor of finite extent is given by a sum of decaying exponentials with a range of time constants. The late stage begins when the term with the longest time constant dominates the response. Graphically, the logarithm of the magnitude of the secondary field versus time tends asymptotically to a straight line in the late stage; the slope of the line gives the late stage decay constant. It should be noted that in magnetizable materials, the alignment and relaxation of magnetic domains is another source of secondary magnetic field decay. In this work, we treat this decay signal as though it were due to an effective (enhanced) conductivity of the material.

Measuring the secondary magnetic field with a coil antenna results in an additional time derivative because the voltage at the terminals of the receiver coil is proportional to the emf induced in the coil by the secondary field. Consequently, the magnitude of confined conductor responses is modified by a factor of $1/t$, augmenting short time constant responses and diminishing long time constant responses.

2. PEMI data processing

PEMI data is comprised of sets of short time series in which the secondary magnetic field decays are recorded as time varying voltage values. The recordings are taken at several stations, usually along a profile or on a grid, providing a set of measurements which is both spatial and temporal. The receiver is synchronized with the transmitter turn-off so that many pulses are recorded and coherently averaged at each station to reduce the effect of ambient electromagnetic noise. Other noise reduction schemes such as synchronizing the pulses to the local power grid frequency or using an auxiliary sensor to independently measure correlated ambient electromagnetic noise have been used in our approach but will not be described here. Instead, we will emphasize the algorithms used in data interpretation.

For convenience and speed, the inversion of PEMI data is done in two steps. First, the time decay is analyzed at each station to determine whether an exponentially decaying response is detected, and if so, to estimate the time constant and amplitude factor of that late stage decay. Once the amplitudes have been determined for all stations, their spatial dependence is used to estimate the location and orientation of the target conductor. The late stage response is simply modeled as

$$R(t) = A(r)\,e^{-t/t}$$

where the amplitude *A(r)* includes the factor of t in the denominator. The challenge with real data is to determine when the decay has reached the late stage, and when the ambient noise level has exceeded the PEMI signal; in this project, selection of the appropriate time interval was usually done by an operator, but the experience gained will facilitate the design of automated detection algorithms.

The approach used to make the estimates of decay constant and target location was to fit the thin ring model to measured responses using a non-linear Damped Least Squares (DLS) optimization routine [Marquardt, 1963], which provides an automated and stable way of finding the “best” fit of the simple ring model to the data. Other optimization algorithms could be used as well, so long as they were able to handle non-linear inverse problems.

3. JPG IV field procedure

The first experiment conducted during the week of April 27, 1998, was a “self-test” in which buried targets were identified by the sponsor, and representative ordnance and clutter items were provided for above ground testing. Inert ordnance ranged from 155 mm projectiles to 20 mm rounds. Buried target zones were surveyed by making PEMI measurements at a few stations in the vicinity of the target; this should be sufficient for basic characterization of the target type. If detailed localization is desired, two perpendicular PEMI profiles centered on the estimated target location are sampled. Spatial density of measurements were determined on the fly; previous experience indicates that data will be collected every 25 to 50 cm directly over the target, and every meter when further away. The power line noise (60 Hz and harmonics) was surprisingly strong (vertical component) at the JPG IV site; commonly, SNR ≤ 0.1 in unfiltered data.

4. Expected performance

Typical accuracy of test target position and orientation estimates are better than 10 cm in depth, 5 cm in horizontal location, 5 degrees in tilt (polar angle), and about 10 degrees in bearing for common detection ranges of up to 5 meters. Previously achieved area coverage rates were limited by the need to lay out a physical grid before taking data, and manually entering station coordinates (including sensor elevation) for each station. This project includes provisions for automating the position sensing of the sensor platform using a local reference point for each target survey. Position sensing will be entirely mechanical, using a compass heading and odometer for tracking in the horizontal plane, and a liquid level system for the elevation. Under these conditions, an average rate between 1 to 5 minutes per station is anticipated, with between 3 and 30 stations per target, leading to between 5 minutes to 1 hour of survey time per target.

IV. SUMMARY

The JPG IV Pulsed Electromagnetic Induction (PEMI) project conducted by the Applied Physics Laboratory, University of Washington, seeks to demonstrate the discrimination and classification capability of the PEMI technique. The project began in November 1997 and work to date has primarily focused on rebuilding and testing the PEMI testbed to render it more suited to field operation. Design and assembly of a new transmitter circuit has been completed, as has the conversion of the data acquisition system from desktop computer and data acquisition instrumentation to a laptop computer with compact signal conditioning. A new sensor platform has been built and includes a simple system for short range automatic position sensing. The preliminary “self-test” at JPG provided an opportunity to conduct a successful test of the system on site, and collect data from representative ordnance and clutter items that will be used in the final demonstration scheduled for August 1998.

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